Superconducting Cavity Development at FNAL

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W.D.Möller, R.Wanzenberg, … (DESY)

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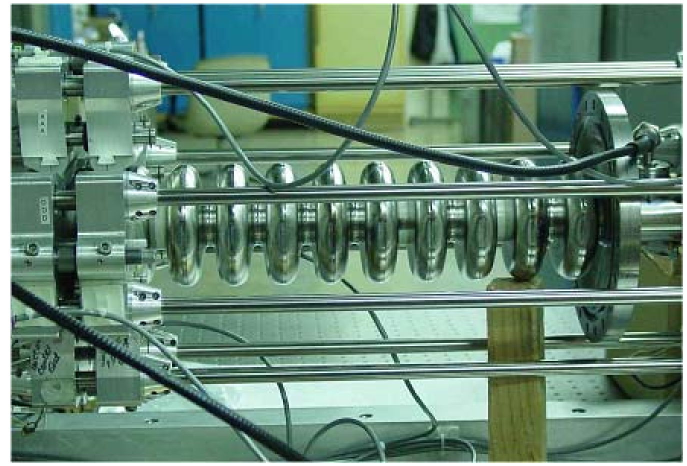
Fermilab Accelerator Advisory Committee
10-11 May 2004

Two 3.9GHz Designs

TM$_{110}$ mode *"CKM"*

K^+ RF separator for $K^+ \to \pi \nu \bar{\nu}$
Bunch profile measurement at zero crossing

B_{MAX} = 80mT E_{MAX} = 18.6MV/m
L_{eff}=0.5m, $P_{\perp}$=5 MV/m

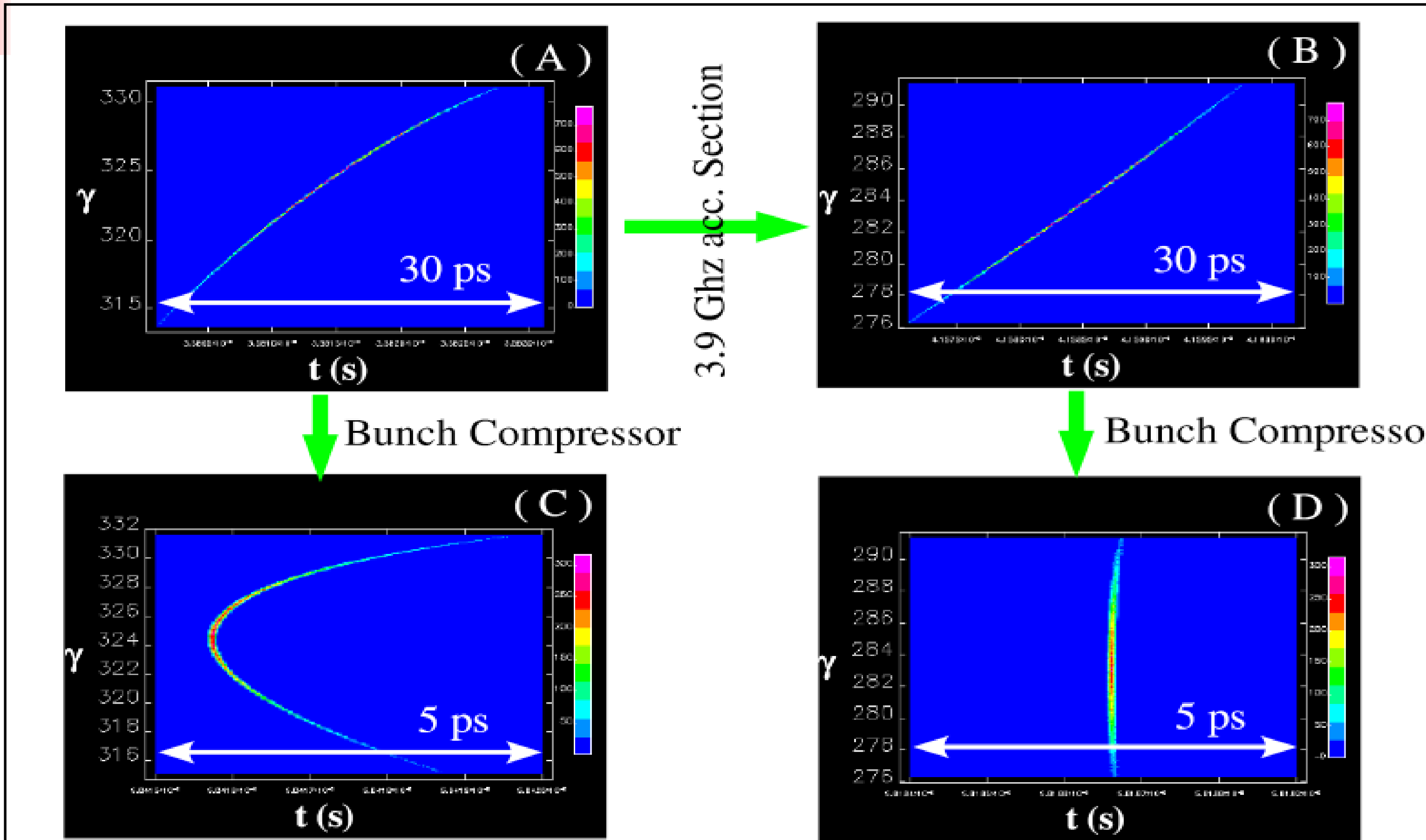


TM$_{010}$ mode
"3rd Harmonic"

Linearize energy distribution within bunch before compression for better emittance

E_{ACC} = 14MV/m
B_{MAX} = 68 mT E_{MAX} = 31.6MV/m
L_{eff} =0.346m

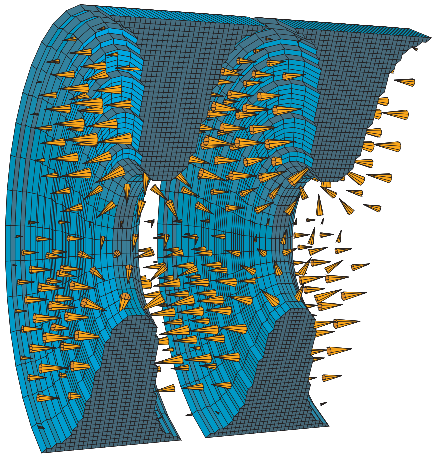
3rd Harmonic cavity to Improve Beam Characteristics in injector



Use of TM_{110} cavity in TESLA bunch compression reduces energy loss and a 2-stage system could permit compression to < 300μm, reducing the "banana effect" - Piot & Decking, FNAL TM-2235

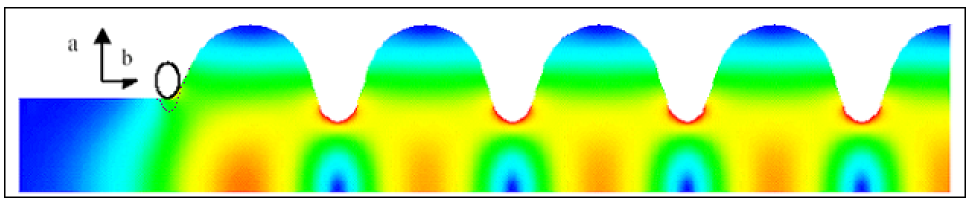
RF Design

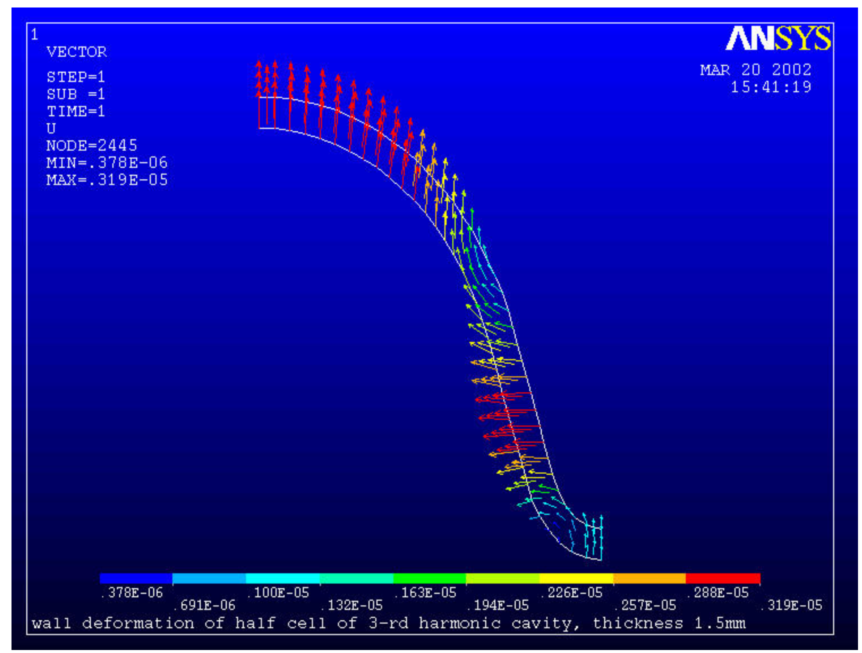
TM$_{110}$



TM$_{010}$

- Basic electromagnetic design done with MAFIA, HFSS, MWS, lumped equivalent element methods
- Interface to mechanical FEMs (ANSYS, IDEAS) custom built





<u>Lorentz force detuning</u>

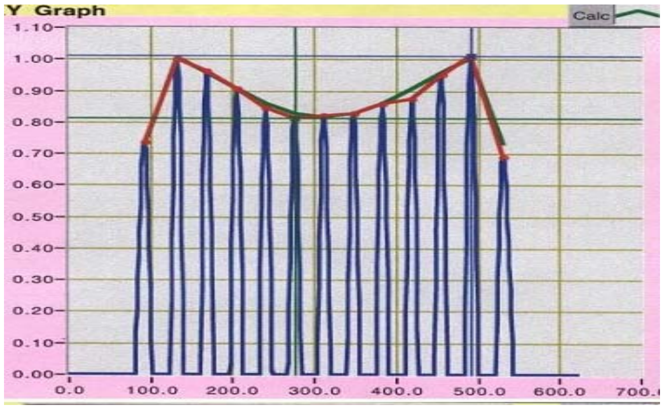
✓ CKM cavity: calculated Δf = 770Hz for 1.6mm thick wall with free ends; measured at Δf = 728Hz.

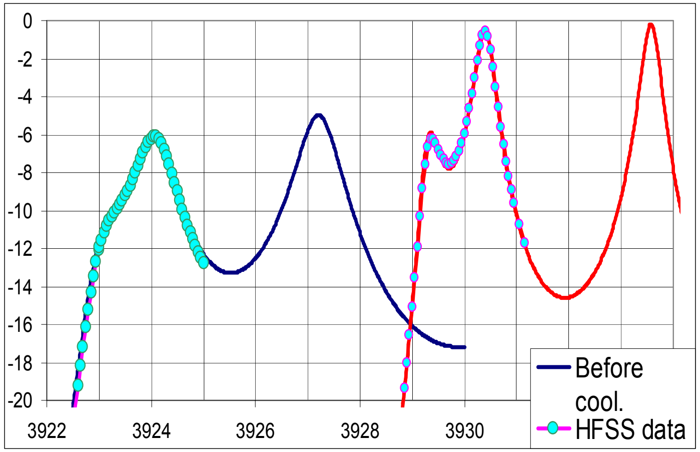
✓ 3[rd] harmonic cavity: Δf = 90 Hz for 2.8mm thick wall.

RF Design

Tuning cavities with overlapping modes

- **First prototype TM_{110} half-cells had large freq scatter**
- **First cavity had π mode and (π-1) modes totally degenerate**
- **Designed mode separation was very close anyway**
- **HFSS predicts "M" type bead pull result for 300K; linear combo of MAFIA eigensolutions similar**
- **At 70K, HFSS gave correct S_{21} vs. f plot, and bead pull result was flatter. Plan to try bead pull at LHe temps.**





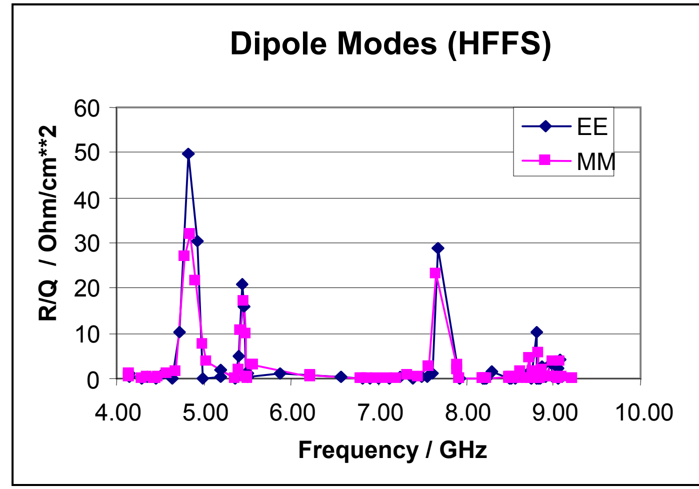
RF Design, HOMs

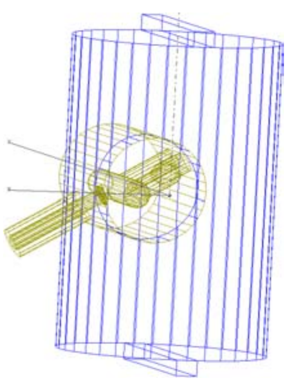
Higher order modes are most critical for TM_{010} cavities; for TM_{110} cavities, worst HOM is a LOM.

Rescaled from TESLA HOM couplers (J.Sekutowicz)

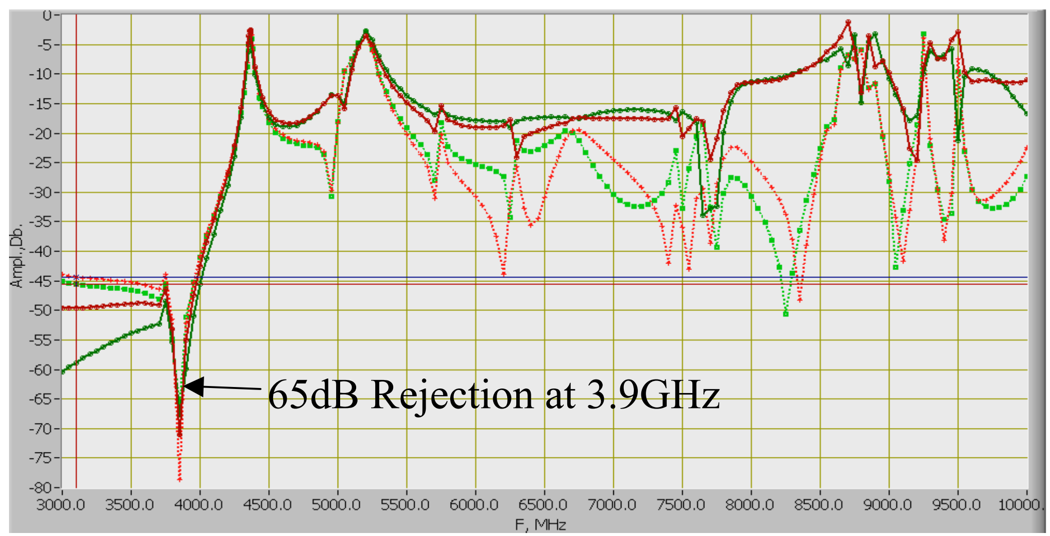
R/Q quantities calculated in collaboration with DESY, using both MAFIA and HFSS

HFSS 3D model used to study cavity excitation by beam as function of frequency

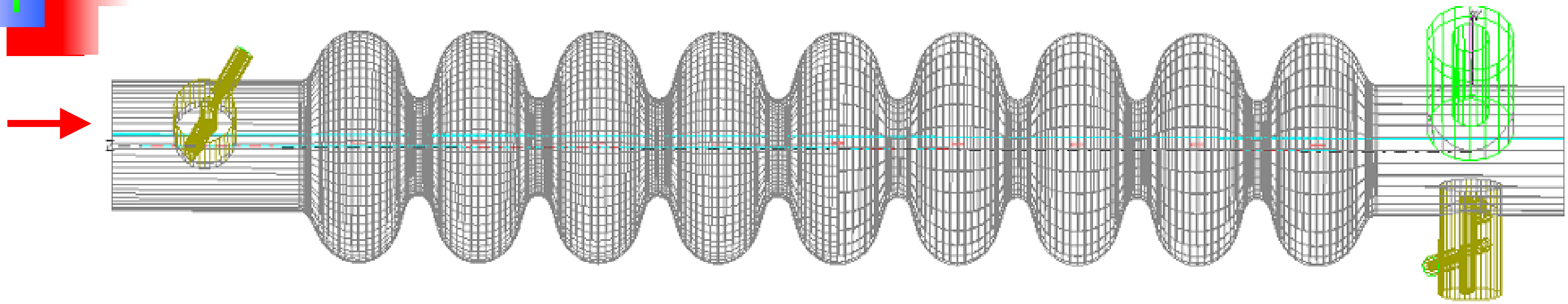




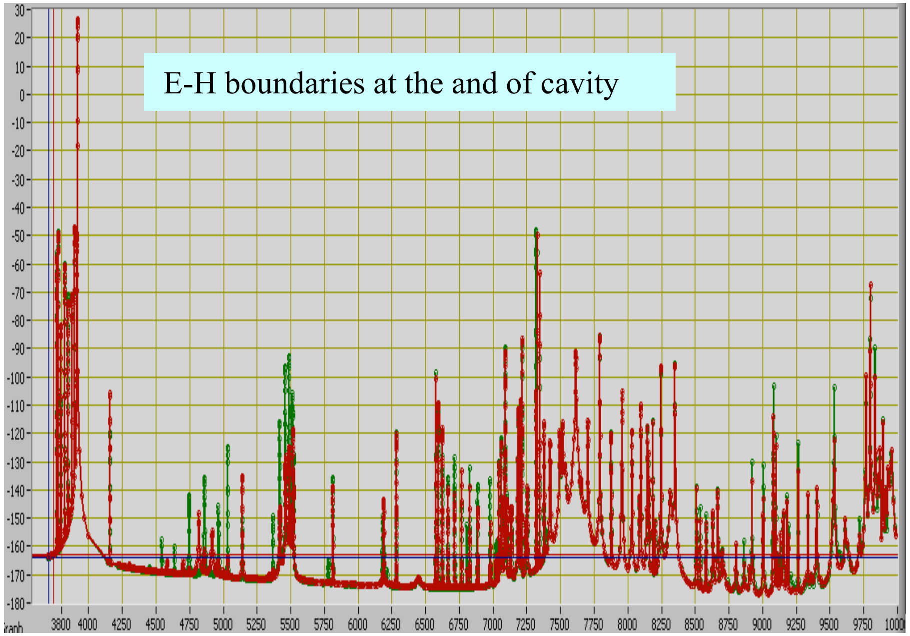
S parameters coupler to beam pipe)

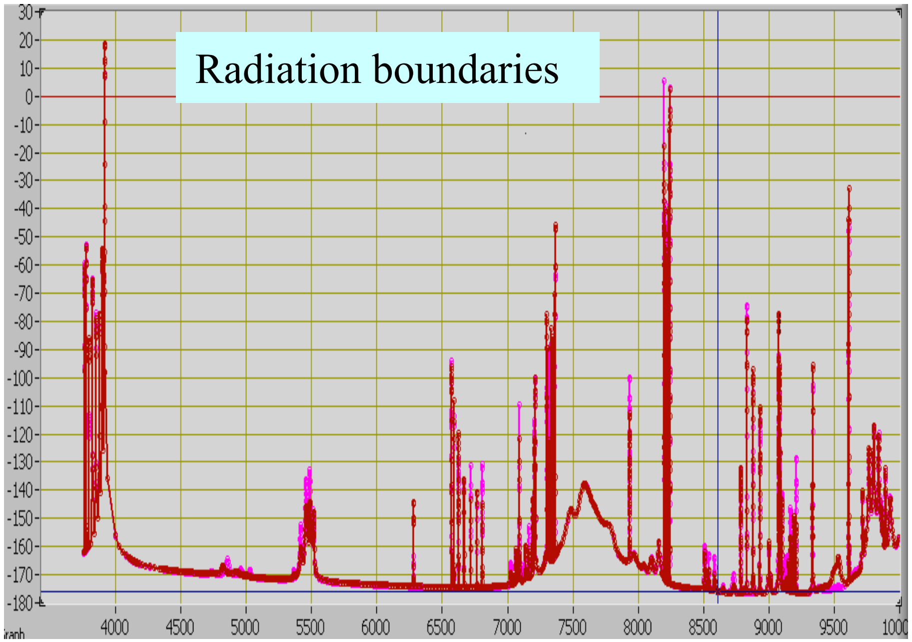


HOM damping

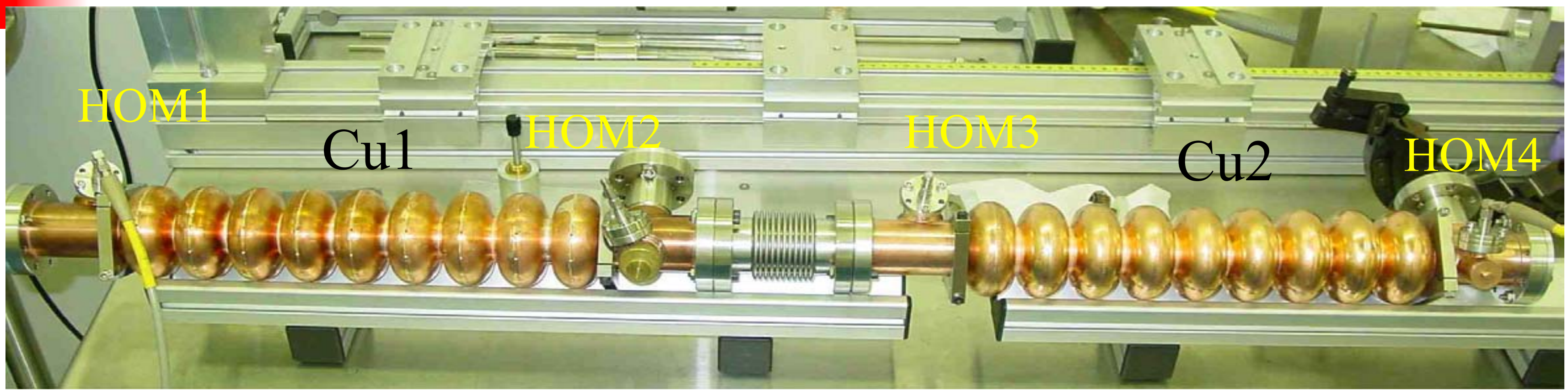


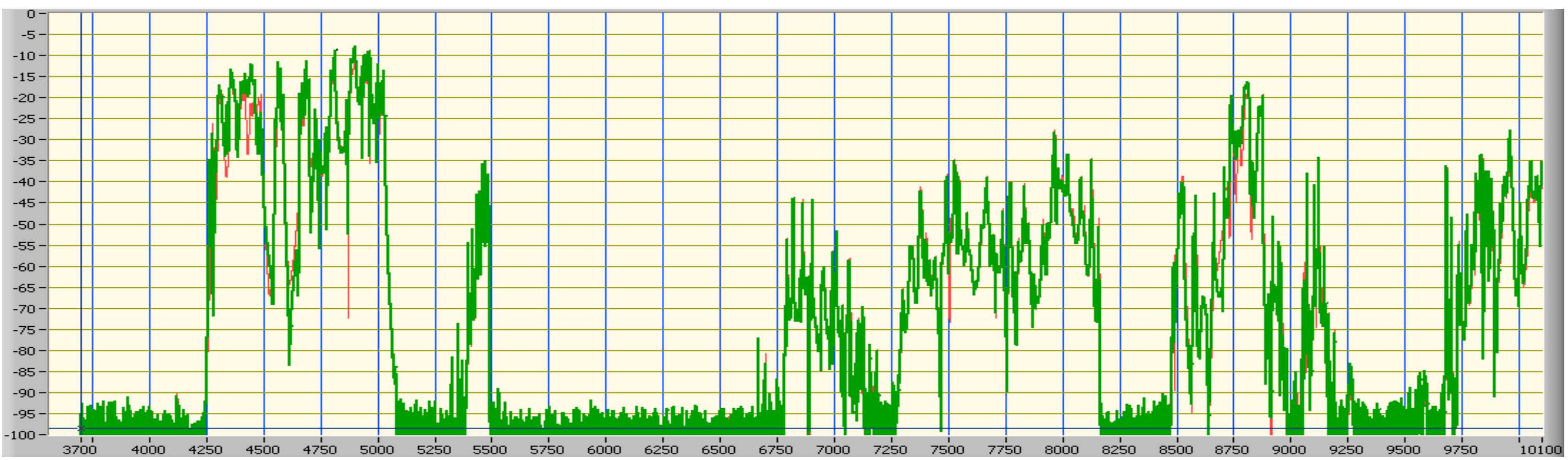
HOMs excited by beam with 2mm off-set in x/y directions (HFSS)





HOM study in a chain of two copper TM_{01} cavities





F=4813 MHz. Qmax=2180, Q2=1160, Q4=890

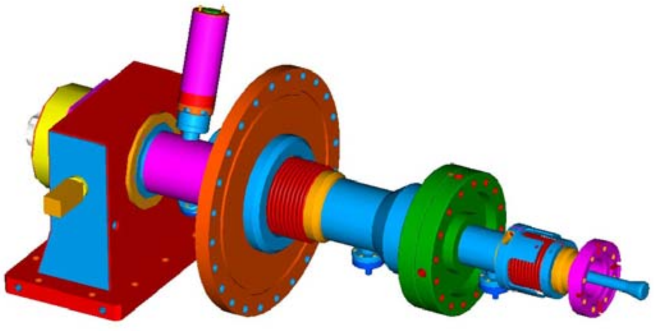
F=4994 MHz. Qmax=26000, Q2=4990, Q4=4320

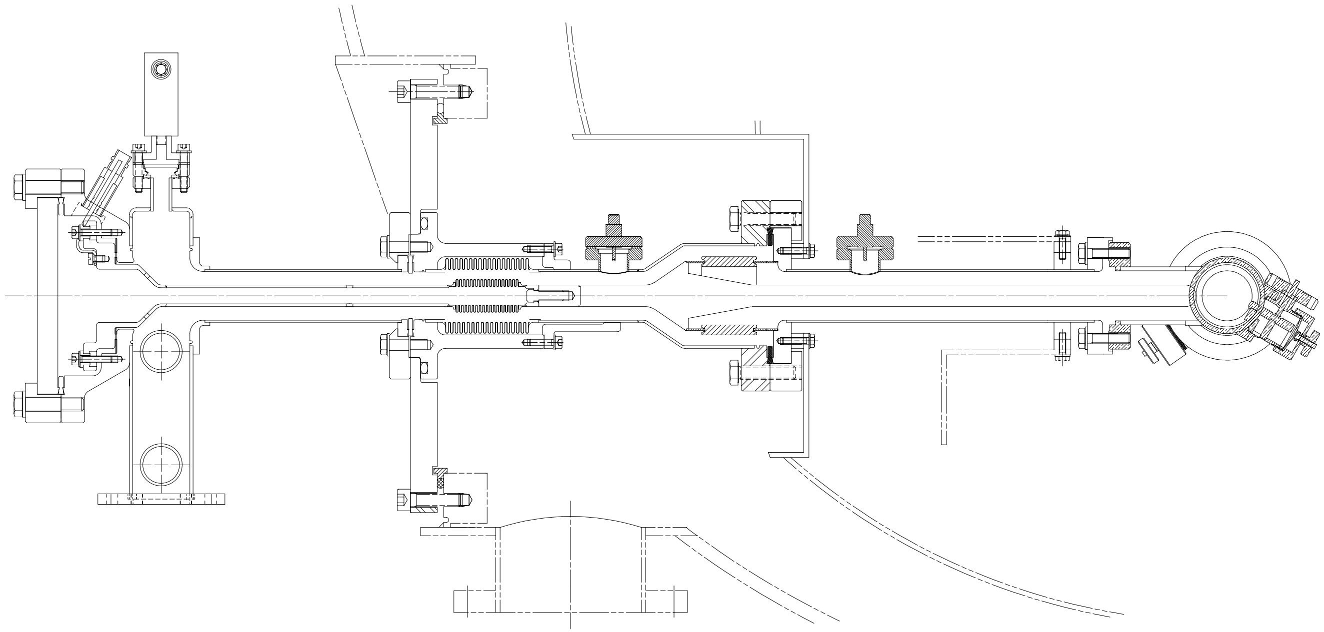
F=5474 MHz. Qmax=28300, Q2=12500, Q4=9300

Power Coupler Development

Initial design was adjustable

Plan to try a non-adjustable version with 3-stub tuner in waveguide

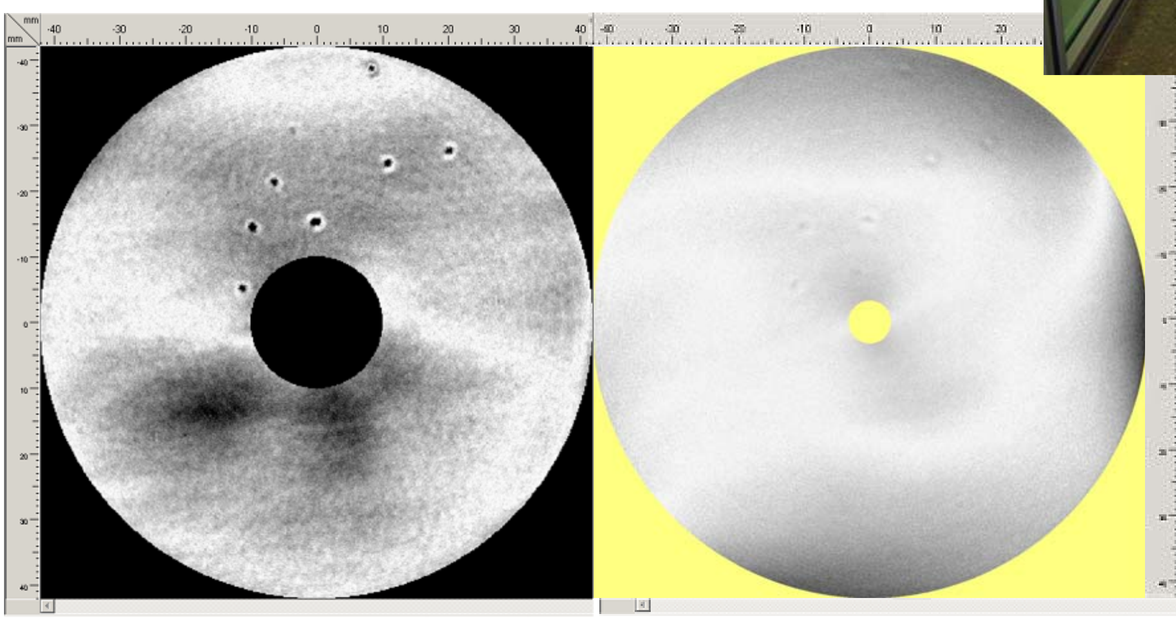




Nb material Control

Eddy Current Scanner donated by SNS

- Good to detect inclusions (100μm Ta, 10 μm Fe, etc.), not enough for pits and scratches.
- Built disk holders for CKM and 3rd harm disks
- Upgrading to improve Scanner resolution:
  - new alignment system, new coils, etc.



Disk 3harm_b1_22_2 scanned at DESY (left) and FNAL (right).

Size of pits ~50-100μm

Cavity Manufacture

- ✓ *We purchase pure (RRR=300) Nb sheet from industry, and DESY has done eddy current scanning for us (planning to scan on site)*
- ✓ *Stamp on site and e-beam weld near FNAL under clean conditions*
- ✓ *RF measurements and profile measurements of ½ cells on site*
- ✓ *We have an on-site vacuum bake facility (1000 C) to remove H_2 and anneal - have not done Titanium gettering*
- ✓ *Field flatness tuning on site*
- ✓ *BCP Acid etch has kindly been done for us by JLab, to be done in collaboration with Argonne*
- ✓ *On-site high pressure rinse with 18MΩ H_20*

Also are contracting with Advanced Energy Systems to build a few cavities both types

1000°C Vacuum Oven

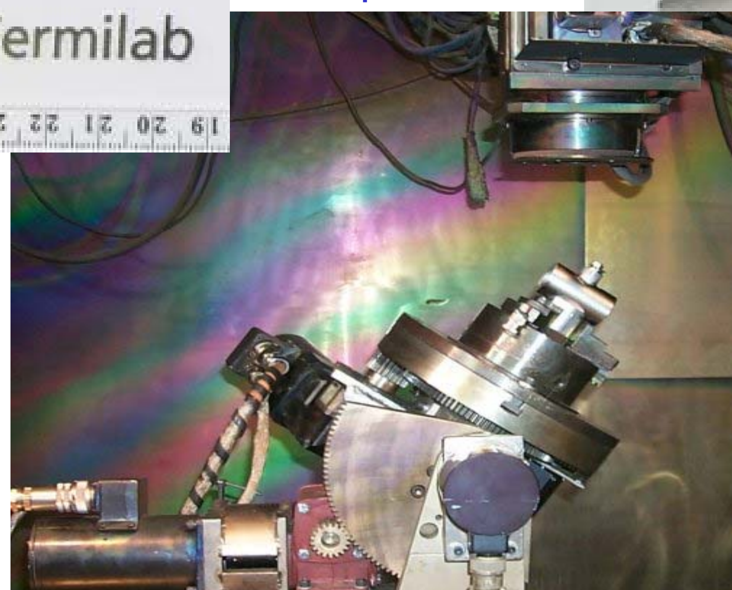
Production. EB welding

Welded dumbbells of the 3rd harmonic cavity

Cut weld for inspection

Test welds on the end-tube group.

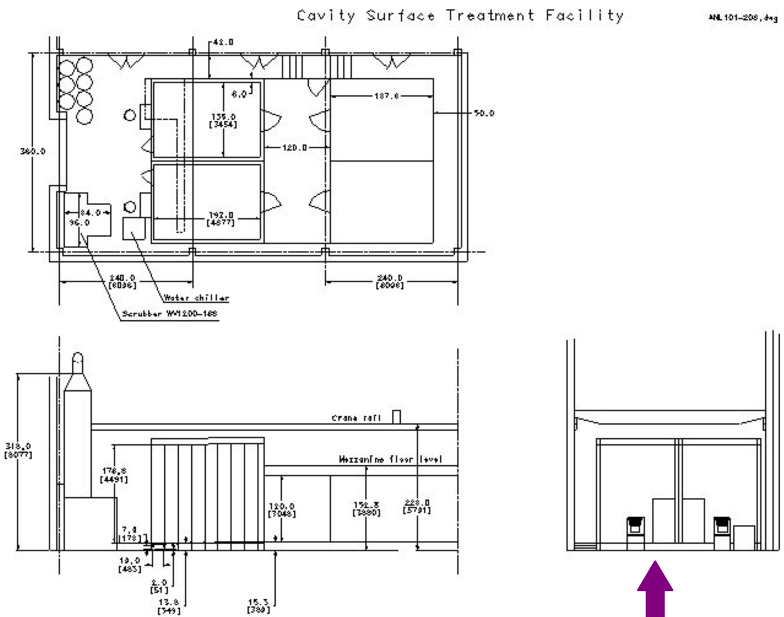
All components (except two flanges were e-beam welded to specify weld parameters.



E-beam welding machine at Sciaky, Chicago.

Chemistry

Short term: Existing ANL facility, JLab



Long term: Joint ANL/FNAL facility

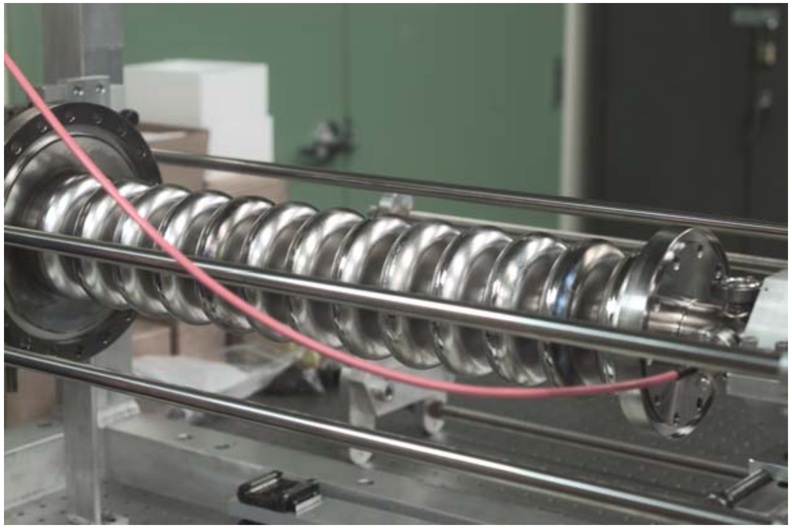
BCP Facility Status

MOCUP @ FNAL

- ✓ Hydraulic system - compete.
- ✓ Control system – is being tested
- ✓ Process tank – in procurement
- ✓ System readiness at FNAL – end of May
- ✓ ANL safety review and commissioning – (need to address some issues like UPW source, clean rooms, building mezzanine).

Cavities Produced

Eight TM_{110} mode cavities have been made, mostly shorter structures, but there is one full 13 cell prototype. One more short structure is in production, and one more 13 cell is planned



In addition to the two copper TM_{010} mode cavities shown earlier, a 3 cell has been made in niobium and a full 9 cell prototype is in production now

Recent TM_{110} Cavity Production

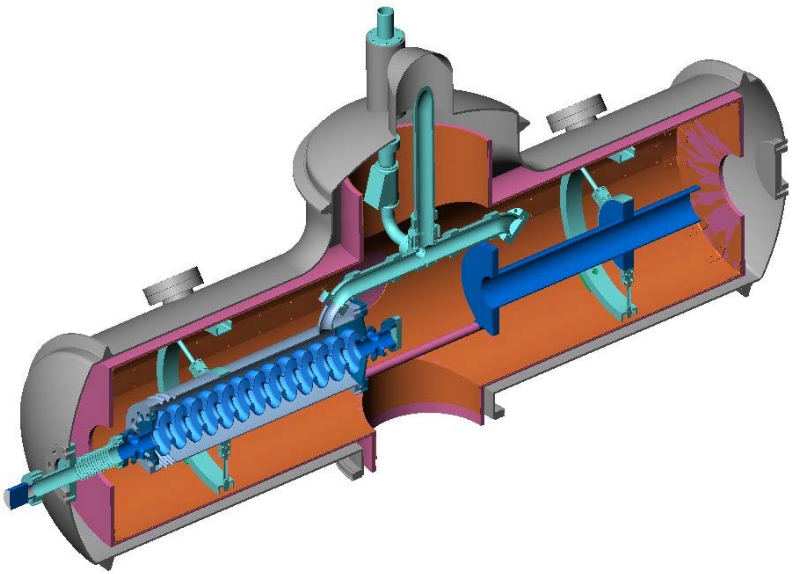
- Cavity made with 1.6mm thick annealed Nb (top left) proved far too soft mechanically

- Made a 3 cell with 2.2mm thick Nb

- Two trial acid-etch cycles at ANL were done on the older 3 cell:
  - Restored high field levels
  - But also very high R_{SURF}
  - Bacteria in H_2O - system sanitized, being retested
  - These cavities will go to JLab for etching and rinsing.

- Cold tests planned for June

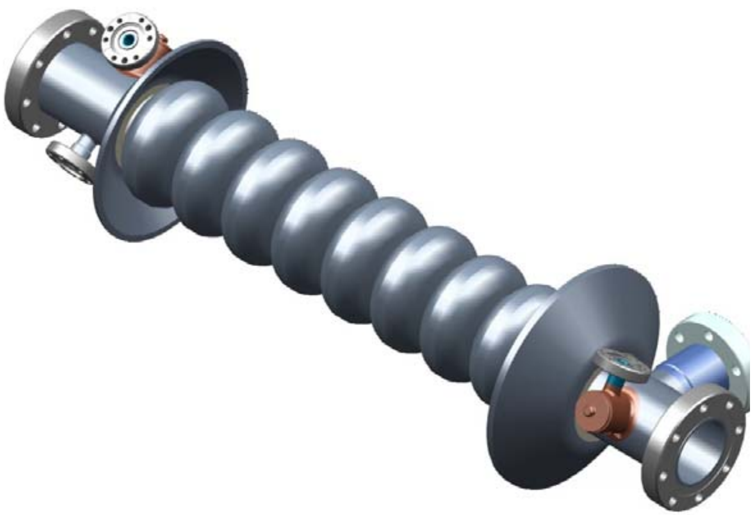
Cryovessel Design & Fabrication

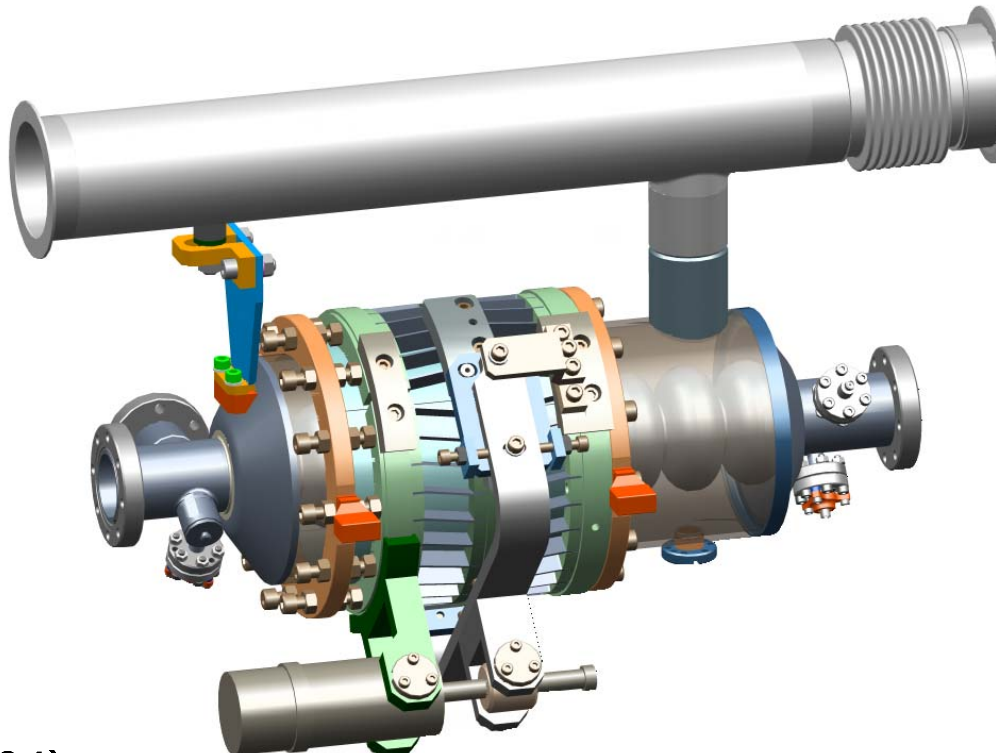


- ✓ LHe vessel built, assembled with 13 cell prototype;
- ✓ Magnetic shielding being annealed now
- ✓ Cryovessel design for TM_{010} / TM_{110} cavities just beginning

Cavity Production. 9-Cell Design Status

TM$_{010}$ cavity





Cavity Production (end of Sept. 2004)

- Half-cells: done, RF measured, ready for welding
- End tubes: components 90% ready, weld tests 95% done, most fixtures are ready
- Tough schedule for e-welding

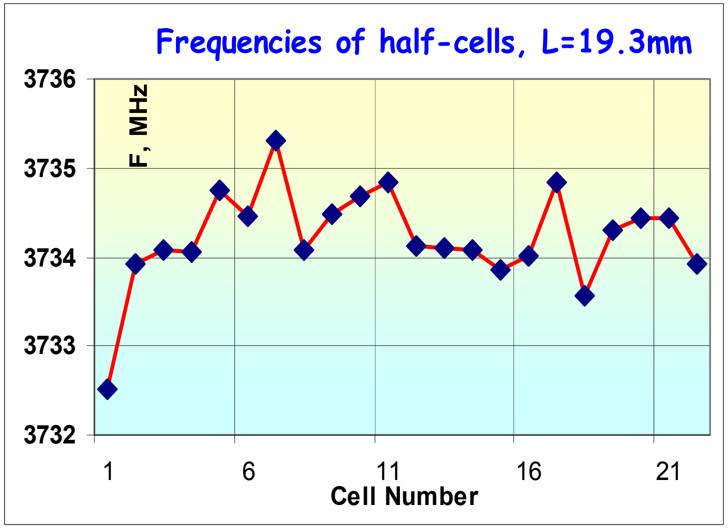
Helium Vessel and Bladetuner

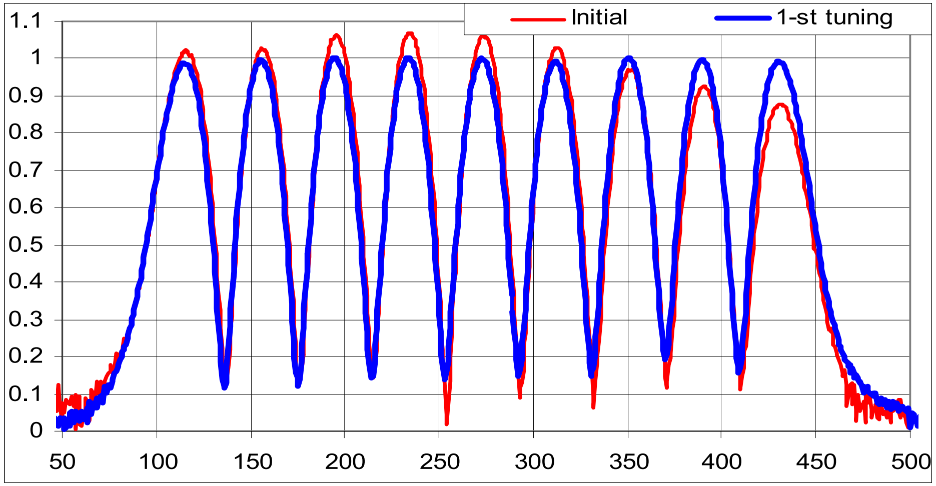
- Drawings: 95% finished
- Procurement: start June
- Ready: End of 2004
- Magnetic shielding - designing

Warm Test Results TM_{010}

FNAL half-cell uniformities and f_0 very good ~50μm ⇔ 1.5MHz

AES half-cells ~3MHz RMS

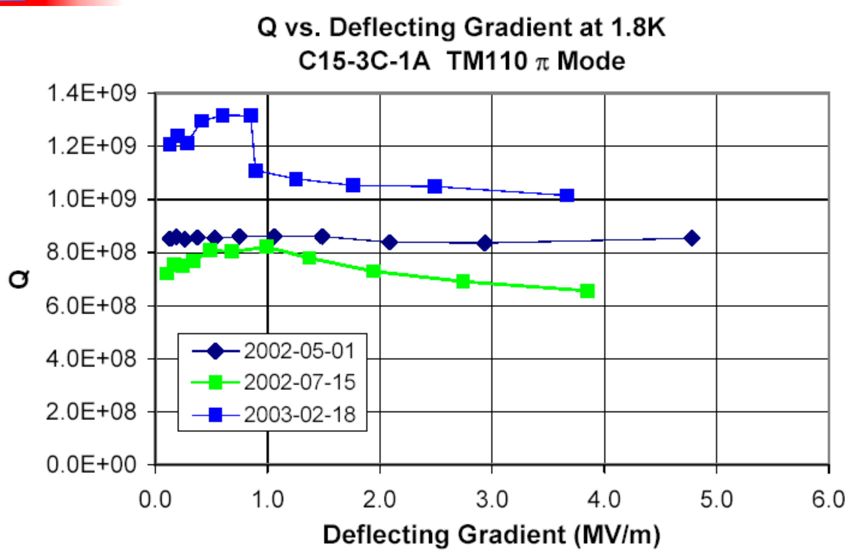




Field flatness before (red) and after tuning.

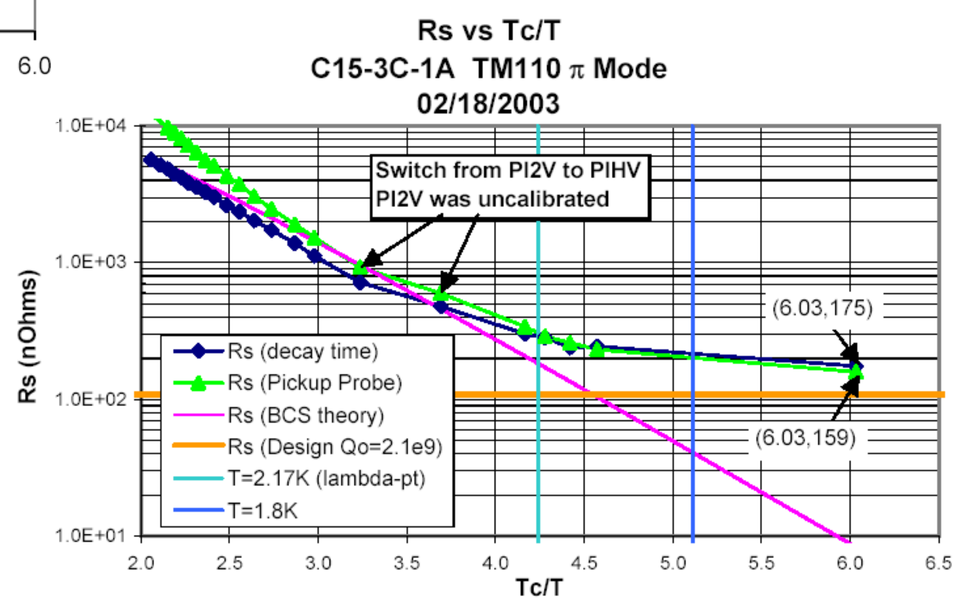
Flatness better 0.5%

Cold Test Results (TM_{110})



Most cold tests done with 3 cell cavity - Acid etch facilities need upgrade for 13 cell test

$P_\perp$ originally ~5.1MV/m but has decreased to about 3.5MV/m with repeated tests. Have recovered 5.4MV/m (but high R_{surf}) with recent acid etch



R_{surf} at T=1.8K design goal is 110nΩ

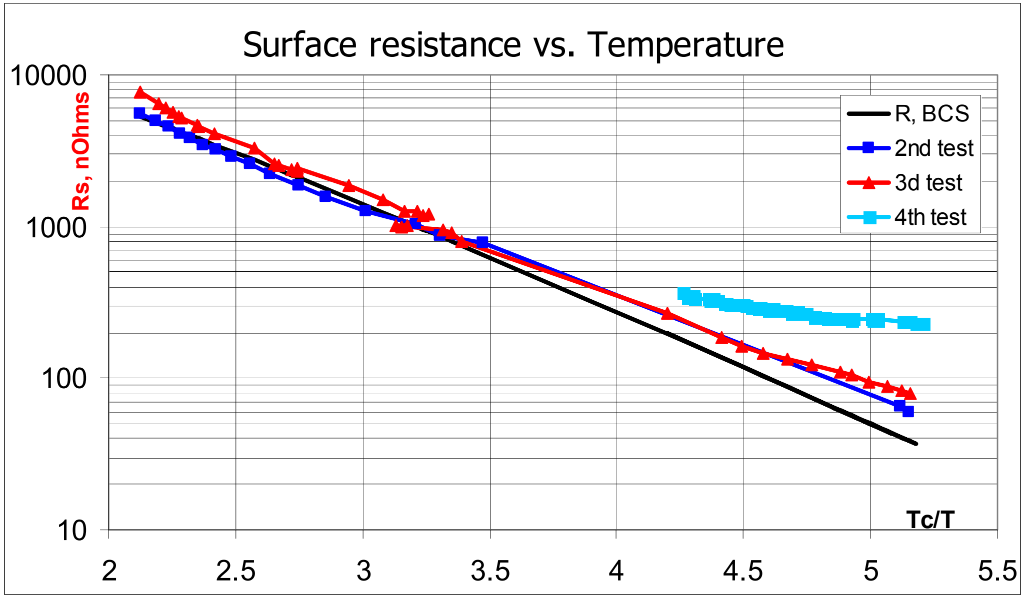
Recently obtained ~160nΩ in TM_{110}, ~65nΩ in TM_{010} ($\Leftrightarrow$126nΩ in TM_{110})

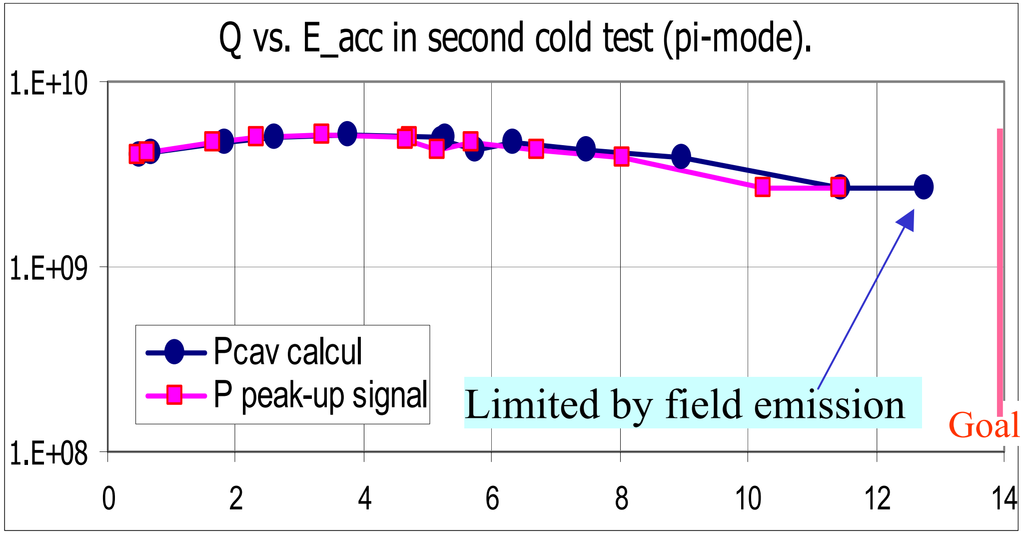
Reason is not clear:

> Residual beam pipe effect?
> Power lost in coupler tip?
> Power in weld area?
> Otherwise wrong κ,R_{SURF}?

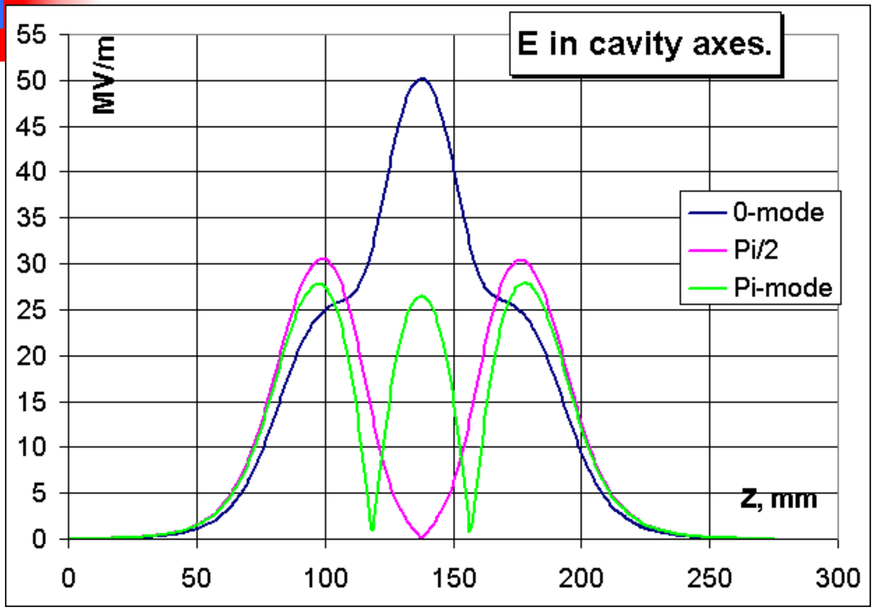
Cold Tests of the 3-cell TM_{010} cavity

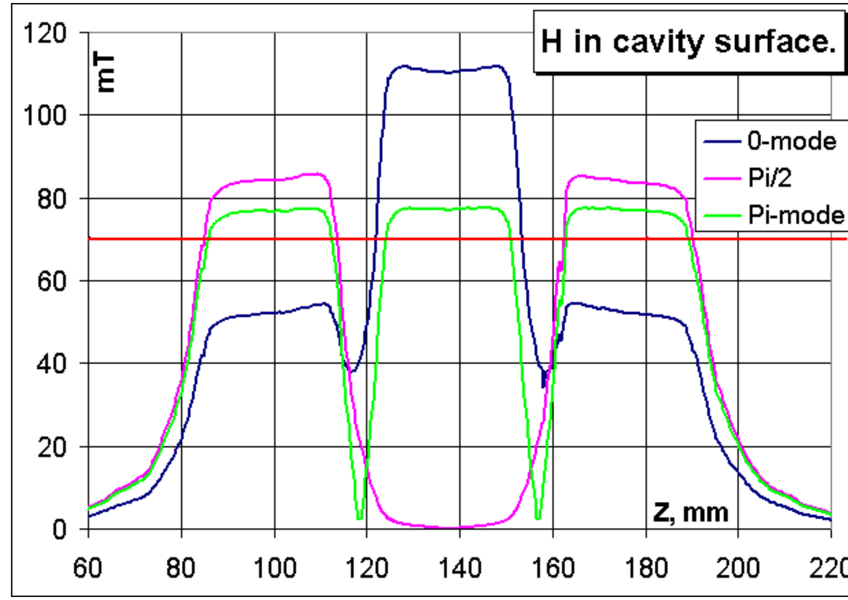
Test done after 140 μm BCP, heat treatment and HPWR





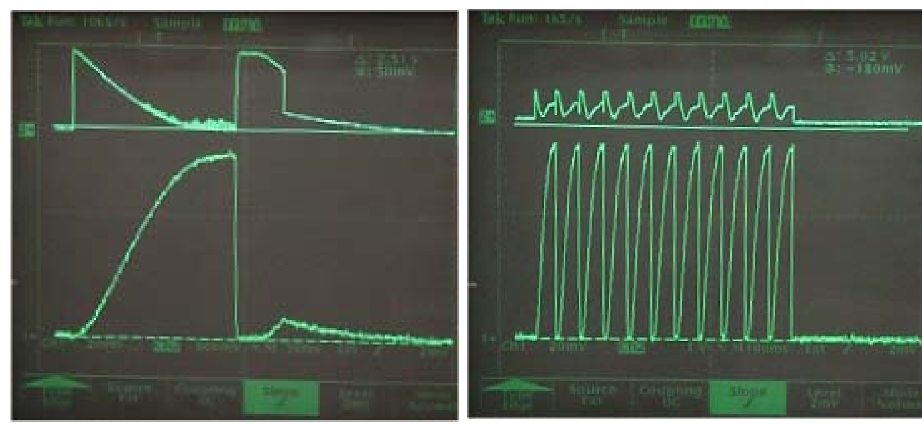
Cold Test of the 3-cell TM_{010} cavity (cont)





Results from the first 3-cell cavity tests

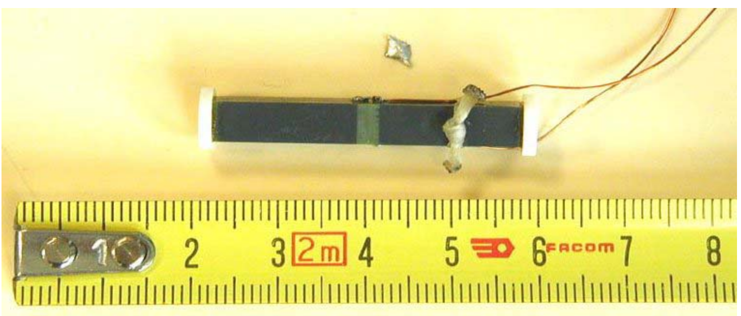
- ✓Reached at T=1.8K R_{surf}~70 nΩ (Q~$4*10^{9)}$)
- ✓ Bmax (mid-cell) = 110 mT => Eacc ~22 MV/m
- ✓ Bmax (end-cell) =78/85 mT => Eacc~16/17 MV/m
- ✓ Field emission limitation (spot on the iris)
- ✓ Q (R surface) degradation vs. test#
- ✓ Plan: 20μm BCP, HPR and repeat cold test



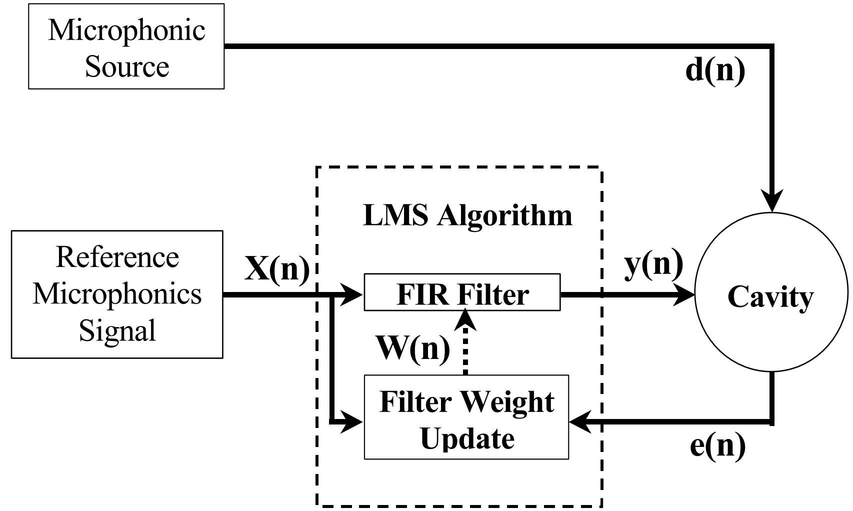
Quenches in short and long RF pulses

Piezoelectric R&D

We have been investigating the use of piezoelectric elements to dynamically adjust the length of the cavities in response to mechanical vibrations, temperature and pressure changes.



At 300K:	Open loop resolution	O [10nm]
	Loads	O [1000N]
	Range of motion	O [10μm]

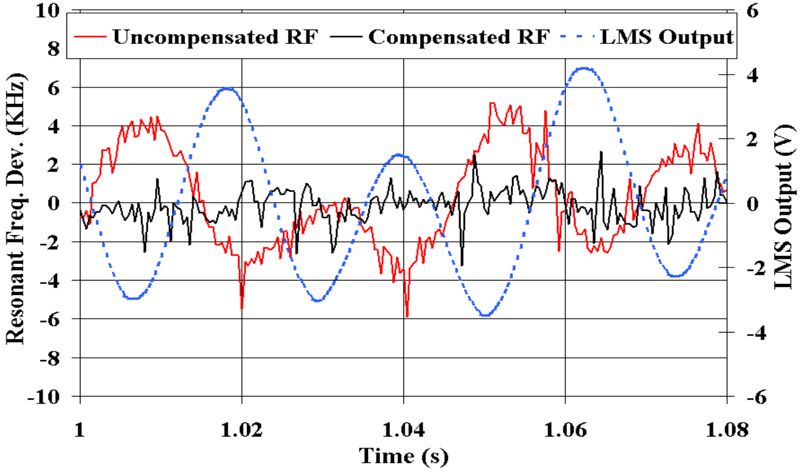


The dynamically adjusted filter tries to match the transfer function of the piezo/cavity system; output y(n) is applied so as to cancel e(n).

For testing, another piezo is used to create sample microphonics

Have been able to get enough canceling amplitude at selected frequencies, but need to understand nonlinearities better

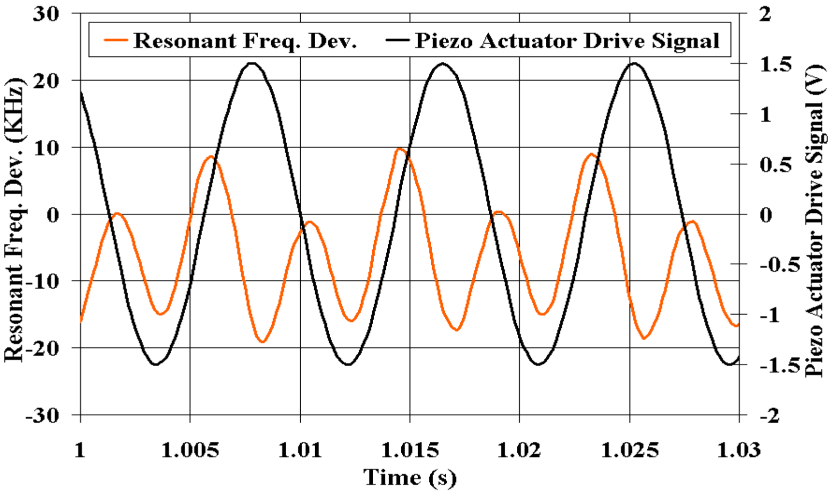
Piezoelectric R&D



Driving the cavities with sum of three sine waves at 15Hz, 27Hz, and 45Hz, where there are known mechanical resonances to the system.

RED curve is FM modulation with algorithm off
BLACK curve is FM modulation with algorithm on

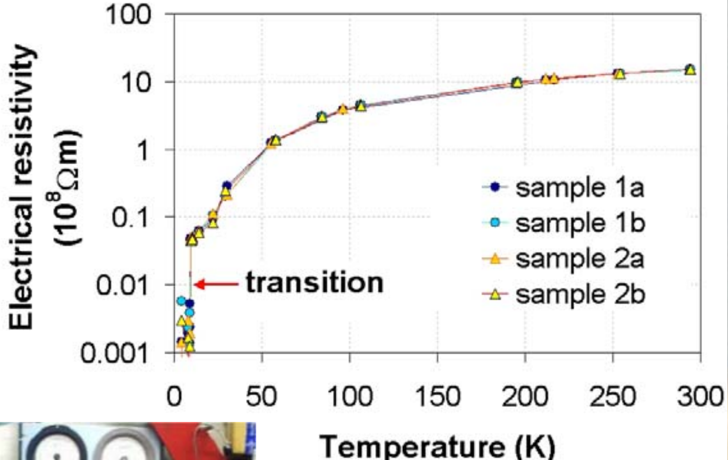
Nonlinear behavior at subharmonics
Algorithm requires linear device to be emulated, but we find that if we drive at an integer fraction of the frequency of a mechanical resonance, the piezo/cavity system is non-linear. *To be investigated*

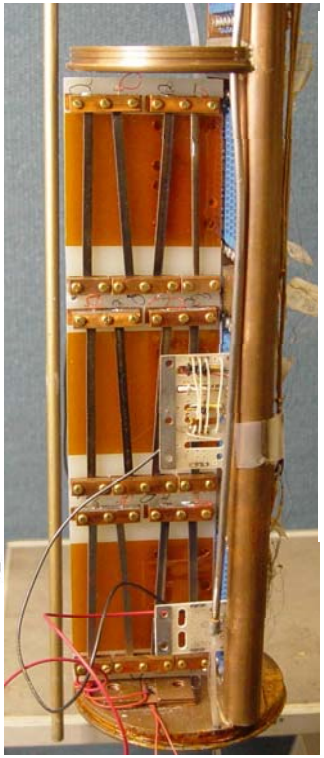


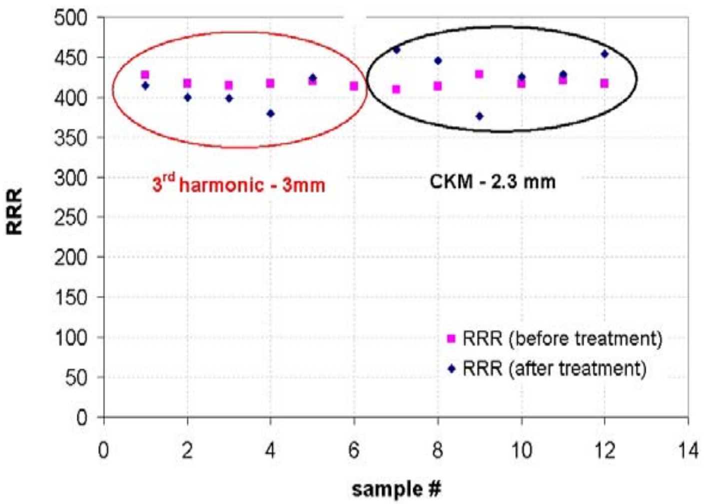
RRR measurements

RRR Measurements:

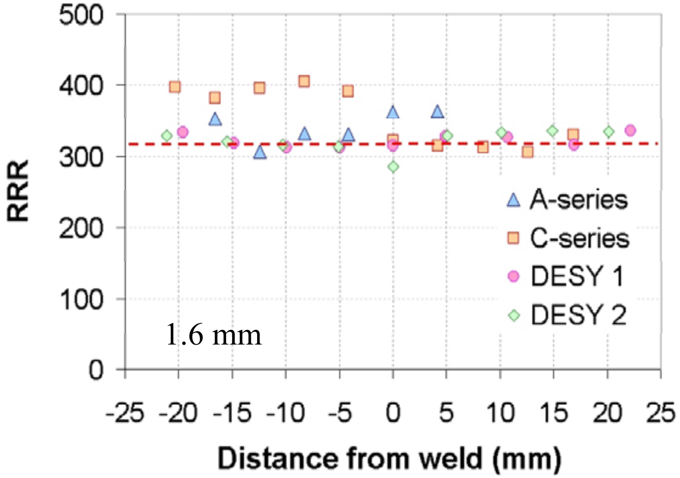
simple, very sensitive to purity, RRR>300







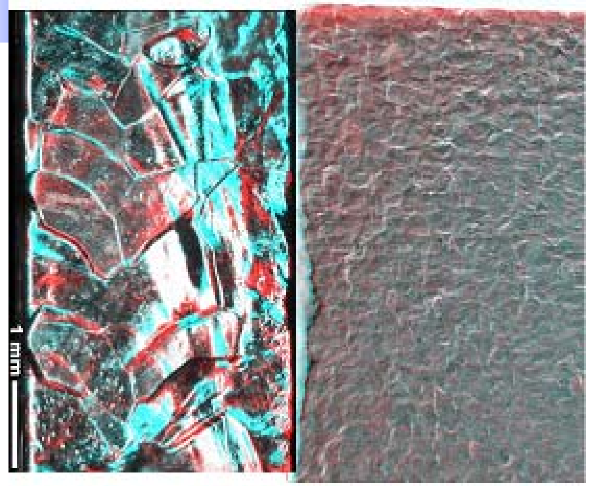
Samples 1.6 mm:	A3	A4	A5
RRR measurement	**284**	**310**	**330**
U-sound pre-clean	**X**	**X**	**X**
100 min BCP etch	**X**	**-**	**X**
800°C bake	**X**	**X**	**X**
20 min BCP etch	**-**	**-**	**X**
RRR measurement	**302**	**110**	**359**



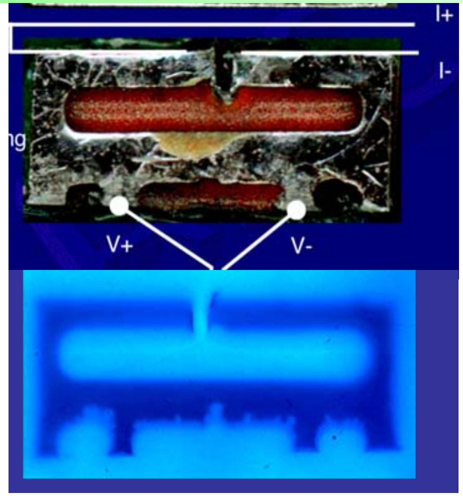
Microscopy Studies

Collaboration Applied Superconductivity Center/University of Wisconsin–FNAL:

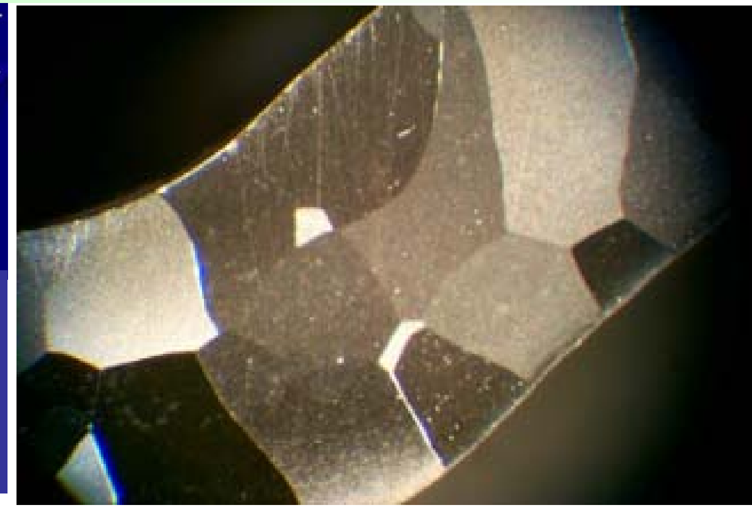
Investigation of the effect of grain-boundaries on the RF surface resistance in Niobium.



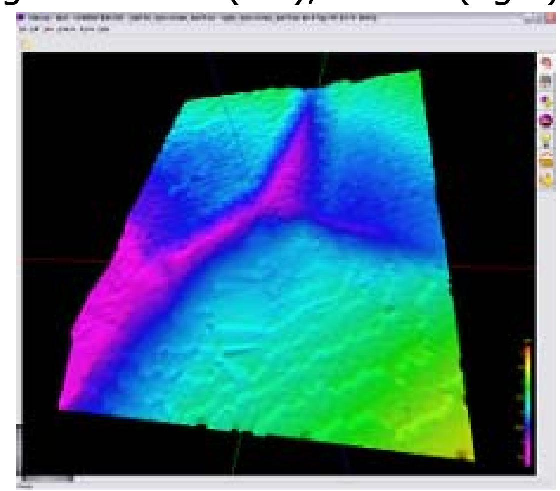
SEM of BCP-etched sample, large grain in weld (left), normal (right)

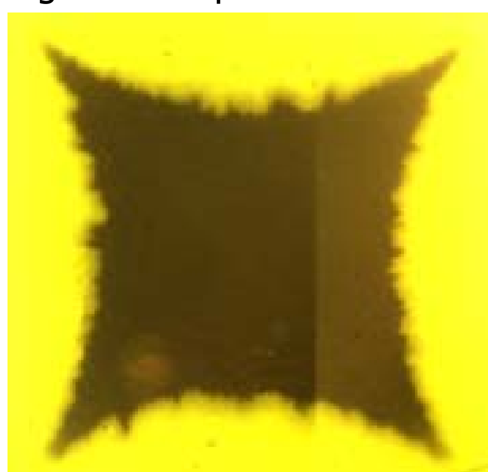


Samples for inter- and intra-grain transport measurements

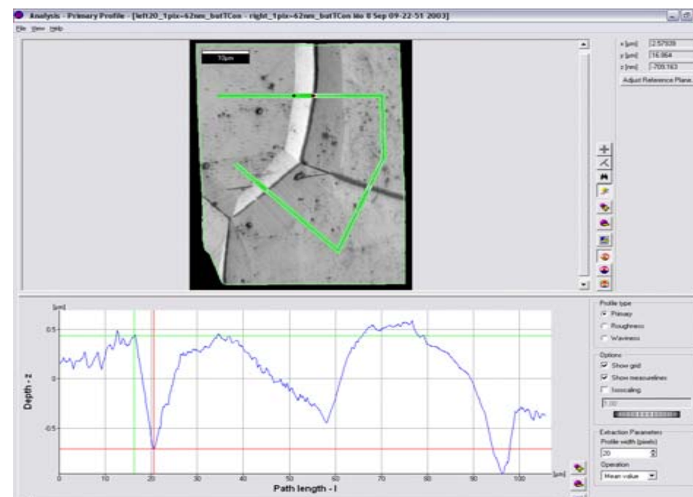


Grain structure in weld sample





Magneto-optical image of 5x5 mm^2 sample in 80 mT field (6 K)



Profilometric measurements in samples

Conclusion

Carrying out the Superconducting RF cavity R&D for these two relatively modest systems has lead us to develop a wide range of design, manufacture and test facilities that provide an excellent knowledge base for the future SCRF LINAC.